The NASA Geodetic VLBI Program

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Prologue

Space geodesy provides unique information about the Earth system ranging from surface deformations to core dynamics to Earth's orientation in space. The three primary global geodetic techniques in operation now - Very Long Baseline Interferometry (VLBI), the Global Positioning System (GPS), and Satellite Laser Ranging (SLR) - define the reference frame for the surface of the Earth, describe the temporal changes in that surface which occur due to natural and manmade influences, and provide direct knowledge and constraints on the atmosphere, oceans, and interior of the Earth by measuring changes in Earth’s orientation in space. It is the purpose of this note to elaborate on what the role of VLBI might be in the NASA Earth Science Enterprise, prompted by the CORE panel discussion of Feb 16, 2001 held at Goddard Space Flight Center.

The capabilities of VLBI have been developed and continually improved over the past 35 years, and NASA has been a major sponsor of the geodetic and spacecraft applications through programs at Goddard Space Flight Center and at the Jet Propulsion Laboratory. It is appropriate that as NASA expands its program in Earth system studies, NASA also continues to take the lead in advancing the space geodetic techniques that will contribute so significantly to Earth sciences in the coming decades.

Introduction

Unlike any other system of measurement, VLBI spans the Universe, from the quasars and galaxies at distances of billions of light years to the core of the Earth. Just as remarkable, it is observations of those remote objects that provides the best estimate of the shape of the interface between the lower mantle and the outer fluid core, halfway to the center of the Earth.

The impetus for developing the VLBI observing system was its potential value to the study of plate tectonics, rotation of the Earth, and the morphology of celestial radio sources. As the technology and physical models have improved, the phenomena that might be investigated and the applications that utilize VLBI have extended in directions previously unimagined. Some examples are:

- the ellipticity of the core-mantle boundary,
- coupling of the magnetic field at the boundaries of the outer core,
- details of crustal deformation near plate boundaries,
- intraplate crustal deformations and post-glacial rebound of the mantle,
- the effect of ocean tides and of El Niño on the Earth rotation rate and axis orientation,
- tests of General Relativity,

- navigation of interplanetary spacecraft,
- measurement of water vapor in the atmosphere suitable for climate studies and weather forecasting, and
- development of the techniques that provided the basis for the high accuracy Global Positioning System analysis.

The use of VLBI for spacecraft navigation is historically noteworthy since a primary application of astronomy from earliest times has been for navigation on the Earth. The scientific goals of the Galileo mission to Jupiter would not have been met without the use of VLBI for determining the trajectory of the orbiter before and after ejection of the atmospheric sampler. Nor would this project have been possible without the many years of development of the technique and technology to achieve the necessary accuracy. Future planetary missions making use of this extremely accurate and efficient navigation system will continue to benefit from the earlier investment in VLBI development that was made “just to do it better”.

In this report we will 1) point out the value of VLBI, 2) indicate the science areas where VLBI is most important, 3) discuss the complementary contributions of the three space geodetic techniques, 4) describe the elements needed for a healthy program, 5) relate these goals to the need for a historical record, 6) indicate the potential for improvement of the VLBI measurements, and 7) suggest how these elements might fit into the evolving observing program.

1. The Value of VLBI

Three qualities of geodetic VLBI argue for an active program. a) VLBI is **unique** for several fundamental measurements of the Earth; b) it is **accurate**, as well as very precise, at better than a few parts per billion; and c) the VLBI system is **stable** over decades at the level of a few millimeters.

The primary recommendation from the CORE panel was for the VLBI program to concentrate on those measurements that are unique to VLBI and to make those measurements with the greatest possible accuracy, given the constraints of the budget and resources.

The unique types of information provided by VLBI are the Celestial Reference Frame (CRF), the scale of the Terrestrial Reference Frame (TRF), and the Earth Orientation Parameters (EOP) UT1-UTC and nutation. The CRF is the defining structure for the orientation of the Earth in the universe. The long baselines that determine the scale of the TRF tie together, and are complementary to, the regional GPS measurements that provide the densification and practical realization of the TRF. UT1-UTC is needed by a host of scientific, civil, and military applications that require knowledge of the orientation of Earth in space. In addition, the variations in EOP can provide information about many important geophysical processes, including the dynamics of the core, anelasticity of the mantle, ocean tides and currents, and the integrated motion of the oceans, atmosphere, and continental water.

Accuracy is judged by both repeatability and by the absence of measurable systematic errors. The precision of VLBI on a global scale is established by the repeatability of measurements of the distances between observatory sites. For separations up to 10,000 km the standard deviation of daily measured baseline lengths about the constant rates due to plate tectonic motion are well described by a fractional error of less than 1.5 parts per billion for data since 1994. This corresponds to an uncertainty in the local horizontal of about 2 mm and in the vertical of about 10 mm on a global scale. Although the systematic errors that limit accuracy are more difficult to determine, all tests that have been applied, such as sensitivity to the minimum observation elevation, are consistent with these values.

VLBI provides a valuable role in other areas as well, through the stability of the system, due in part to its independence from Earth's gravity field. VLBI measurements of the 1.24 km Haystack-Westford (Massachusetts) baseline give an upper limit to the rate of change in all coordinate directions of 0.5 mm/yr (95% confidence interval) over 15 years (Herring, 1992). This establishes that VLBI antennas are capable of the high stability required for the reference frame. Measurements of polar motion will also benefit from this stability, with VLBI providing, at a minimum, the long-term accuracy, since it is independent of changing satellite design and constellations, and GPS providing the more dense temporal coverage.

2. Unique Science Capabilities

Measurements of the variation of the Earth’s angular rotation rate and the direction of the rotation pole are important because these quantities are a measure of the dynamical exchanges among the Earth’s “spheres”, the ionosphere, atmosphere, hydrosphere, cryosphere, lithosphere, aesthenosphere, and core. VLBI is unique among the space geodetic techniques in being able to measure these quantities relative to an inertial frame, which is provided by the celestial radio sources at the far reaches of the universe. Thus, it is sensitive to changes in the distribution of the solid, liquid, and gaseous mass of the Earth that produce changes in these motions. This allows measurement of the response of the Earth to forces applied to it and inferences to be drawn about the properties of the Earth that produce these responses when the driving forces are known. The driving forces might be the changing attraction of the Sun, Moon, and planets, solar flares, large earthquakes, seasonal and non-seasonal variation in the atmospheric and oceanic circulations including ENSO variations (the El Niño phenomenon), surface water redistribution, or even construction of a large dam (e.g., Three Gorges in China) and the accumulation of water behind it. The properties that can be deduced include the inverted-barometer interaction between atmosphere and oceans, mass loading effects, rheology of the mantle, and the degree of coupling between the mantle and the core at various timescales.

The NASA Solid Earth Science Working Group, headed by Sean Solomon, has posed several overarching science questions. The investigation of most of them will rely on geodetic measurements, and some can be answered directly and primarily by using VLBI. Others rely on VLBI for the accuracy of the reference frame within which the measurements are made. It is this reference frame infrastructure that must be maintained and improved if the advances of the next twenty years are to be realized. Although most of the specific programs proposed involve techniques other than VLBI, such as GPS for the densification of the measurements for plate boundary deformation studies, one cannot overestimate the importance of the global reference frame, whose scale and stability are determined by VLBI.

One of the most exciting scientific results from VLBI since the verification and refinement of plate tectonic motion has been the determination of the shape of the interface between the core and the mantle. The dynamic oblateness of this boundary can only be determined using the long-term, high-accuracy series of nutation measurements provided by VLBI. More recently, the continuation and improvement of this nutation series has now allowed the direct detection of the retrograde free-core nutation (RFCN) (Chao et al., 2001; Herring et al, 2001) and inference of the radial magnetic field strengths at the inner and outer core boundaries (Mathews, Herring, and Buffett 2001 (MHB); Buffett, Mathews, and Herring, 2001). Furthermore the best measurements for determining the anelasticity of the mantle at the tidal periods appear to be the fortnightly variations in UT1-UTC, accessible only to VLBI.

The amplitude of the RFCN is variable, but the source of the forcing torques is not known. Therefore the RFCN must be monitored in order to provide the most accurate values for the Earth's orientation, and this can only be accomplished by VLBI.

3. Complementarity of Techniques

The three principal geodetic systems are VLBI, SLR, and GPS. Each of the measurement systems has unique attributes, but none can provide everything that is needed for a practical global geodetic observing system, nor would it be desirable to restrict the program to one system since observations at the cutting edge of accuracy require verification by independent means.

VLBI and laser ranging to Earth orbiting satellites (SLR) and to the moon (LLR) are the original adaptations of the new science and technologies of the 1960's - atomic frequency standards and lasers - by the traditional science of geodesy. As enumerated above the benefits of VLBI are its unique contributions, accuracy, and stability. SLR utilizes high orbits and dense, clean satellites to provide the most accurate measurements of the geocenter. The Global Positioning System, while a creation of the military, has been enhanced primarily by the scientific community to a level of precision comparable to VLBI and SLR. In addition, due to the relatively inexpensive initial cost and to the demand that has arisen from both scientific and commercial interests, GPS has achieved a spatial coverage that, along with the continuous operation of the permanent installations, has created entirely new applications for this geodetic instrument.

The critical measurements that allow the combination of the techniques to the benefit of all are the surveys of the relative positions of the VLBI, SLR, and GPS reference points at all of those sites where two or more are collocated. These surveys must be done with conventional techniques to an accuracy of one millimeter or better in order to maintain an overall accuracy of 1 mm on a global scale.

From the point of view of geodesy, each technique has unique or primary contributions. VLBI uniquely provides the fundamental terrestrial and celestial reference frames and the rotational orientation of the Earth in that system; SLR provides the most accurate tie of the terrestrial reference frame to the center of mass of the Earth; and GPS provides the spatial and temporal densification that has allowed the utility of the high-accuracy system to become so widespread. The three systems overlap in many of their contributions in terms of precision and significance, and it is this overlap that provides the confidence that turns the precisions into accuracies. For example, all three techniques achieve centimeter-level precision in spatial location. Both SLR and GPS obtain the coordinates of the geocenter for the ensemble of observing sites. VLBI and GPS measure polar motion with similar accuracy.

Whether classified as complementary data or as verification information, simultaneous measurements to be used for intercomparison are a valuable investment of resources. The recent report (Rothacher et al 2001) of detection by GPS of previously undetected harmonics of the diurnal variation in UT1-UTC indicates concern whether the signals are of geophysical origin or a manifestation of the modeling of the GPS analysis. A careful evaluation should be made of the amount and quality of VLBI data that would be needed (or perhaps exist already) to either confirm or set limits at the specific frequencies of the sub-daily signals.

The other important component of geodesy is the gravity field, which is obtained from the tracking observations by SLR and GPS, from satellite altimetry measurements, such as Topex/Poseidon, and from ground-based gravimetry. Gravity measurements and height change measurements must be used together to understand the physical basis for apparent changes in height and gravity. A clear example is the combined program in Greenland to try to understand the potential impact of changes in the ice cover on global sea level change and on climate. Though the direct measurements are made by GPS, the rates are tied directly to the scale of the Terrestrial Reference Frame and rely on the long-term accuracy of that scale as determined by VLBI.

4. Elements of a Healthy Observing Program

A healthy program has several equally important components. 1) regular, reliable, high-accuracy results; 2) continual improvement; 3) verification.

A strong operational program should provide the most accurate observations that can be produced within the available funds. The backbone of the geodetic VLBI program, which provides the long-term record of the Earth's rotation, is the weekly series of NEOS sessions sponsored jointly by NASA and the US Naval Observatory. The series is characterized by consistency, which is achieved by utilizing the same basic set of VLBI sites, and by timeliness, which requires a twenty-four hour observation every seven days and processing by the VLBI correlator as soon as tapes arrive. The accuracy of the results is the best that could be achieved at the time NEOS was initiated, given the required commitment to once per week observing. This series of measurements, along with its predecessor IRIS observations and the NASA-initiated and internationally supported R&D and CORE sessions, have provided the majority of the data for the new MHB2000 nutation series (Herring, Mathews, and Buffett, 2001) and geophysical model (MHB) that provide important new insight on the geometry and magnetic field of the inner and outer cores.

Efforts should be made to continuously improve the technique. These should include activity in the areas of observation strategy, technology, modeling, and analysis. The observation program should involve a series of experiments to evaluate both the expected improvements, due either to hardware improvements or to innovative observing or analysis methods, and the feasibility of new procedures. For VLBI these might include the use of phase delays, lower elevation observations, different allocation of frequencies, etc. These observations might also be planned to provide significantly higher accuracy for a limited period of time that cannot be sustained by current resources. Among the best VLBI data are the CONT series of experiments. Each series used a single set of the best stations available at the time in order to obtain data either for a contiguous period of up to two weeks or spaced to sample data for periods from a few days up to seventy-seven days. The data from CONT94 have probably provided the greatest amount of information of any thirteen days of VLBI data due to the careful planning that preceded the measurements and to the subsequent analysis, generated because of the high quality of the data.

Another beneficial area in which to seek improvement is technology. Continual technology improvement is the basis of all experimental advances and can provide both better accuracy and more rapid delivery of results. For the global geodetic VLBI program the technology advances have been due to the leadership of the VLBI groups at Goddard Space Flight Center and at the MIT Haystack Observatory operating under a NASA contract. The implementation of these projects has been the product of large international collaborations involving many countries and agencies. The current Mark 4 correlator, an evolutionary step beyond the Mark 3, which was developed under NASA sponsorship, was a collaboration among NASA, US Naval Observatory, the Smithsonian Institution, and agencies from Germany, the Netherlands, and Great Britain. Current technology emphasis is aimed at two initiatives. First is the recently initiated Mark 5 disk-based data acquisition system, which will benefit the science through better sensitivity while reducing costs and improving reliability. Development and implementation will involve the contributions of at least seven agencies in four countries. Second is the use of high bandwidth optical fiber communication for real-time VLBI, first demonstrated by the Communications Research Laboratory of Japan. This technology is being developed by Haystack Observatory, GSFC, and the MIT Lincoln Laboratory as a collaboration among US agencies, including NASA and DARPA. Successful implementation of this system will further decrease delivery time, in particular for Earth Orientation Parameters. Initially this will primarily benefit users of the Rapid Service EOP data, but can open the door to further cost reduction through unattended operation and elimination of shipping of the recording media.

Finally, it is necessary to validate the quality of the data. This can only be done by allocating resources both for comparisons with measurements by other techniques (GPS, SLR, and conventional surveying) and for intra-comparisons within each technique. These intra-comparisons should be both among analysis techniques and between simultaneous but independent observing sessions. The analysis intra-comparison is one of the primary functions of the three Services, the IVS for VLBI, the IGS for GPS, and the ILRS for SLR, and has provided significant improvement by directly comparing the results of different analysis centers and by providing combined results as their products. Intercomparison is then obtained by the regular combination by the IERS of the results of the three Services. In terms of internal technique validation, VLBI has demonstrated how important it is to make direct intra-comparison within a technique by conducting concurrent observations using completely independent networks and analyses. For the unique products of VLBI, this is the only means of verifying the claimed accuracy of the results. For all of the techniques such a program will enable a more quantitative evaluation of the formal uncertainties.

5. Historical Data Record

NASA recognizes the importance of maintaining long-term accurate historical data sets. This has become especially evident in the studies of climate variation and sea level change for which the accuracy of measurements is generally more important than the short-term precision.

The scientific value of observational data evolves. When the data are first taken, they are used to improve the parameters of existing models, making use of ancillary data from other fields. The quality of the data is evaluated based on the goodness of fit to the current models. Some time later those same raw data will contribute to the estimation of parameters in a more complete model with additional data, and the goodness of fit for those original data will be better.

An important facet of the VLBI data analysis is the opportunity to re-analyze the entire VLBI data set with more accurate models as they become available. Examples of this are improvements in the nutation series, in the way the atmosphere is modeled, and in our understanding of antenna modeling deficiencies. For example, the evaluation by Herring et al (1991) of the realistic uncertainties in the nutation estimates used for detection of the RFCN indicated a 'floor' of 360 μas and a multiplication of the formal error by a factor of two. Re-evaluation of those factors *for the same data* (1980-1989) by Herring, Mathews, and Buffett (2001) saw a reduction of the floor to less than half the initial value and the multiplicative factor to less than 1.5. These apparent improvements in the quality of the original observations are due to the maturing of all of the models through the addition of subsequent observation and through advances in other fields, such as the treatment of the atmosphere and oceans.

Every measurement made for the geodetic VLBI program will become part of the historical record and will be used by generations to come. Since the measurements themselves cannot be improved retroactively, it is important to obtain and improve the observations that provide these data now rather than later.

The rheological properties of the Earth can be investigated by geodetic observations at many time scales, from the high frequency response by seismometers, through diurnal, fortnightly, and annual periods, to the decadal and longer variations in EOP that are made possible by the stability of the VLBI system. Although the accuracies and precisions of observing systems will improve with time, data must be taken at all time scales to make a significant contribution. Furthermore, much is to be learned from non-periodic excitation of the Earth, for example by post-glacial rebound and large earthquakes, but to understand the response to such episodic events, the underlying spectrum must be well known. This requires sufficient observations to have been made at comparable response times and spatial scales to know what is expected in the absence of an episodic event.

Two good examples of the importance of historical data are 1) the explanation for the excitation source of the Chandler wobble recently proposed by Richard Gross, and 2) the derivation of geophysical parameters of the core from nutation measurements over the last sixteen years by VLBI, as mentioned above.

The Chandler wobble has long been known to differ in frequency from the theoretically derived value, but only recently has the source of excitation been demonstrated to be fluctuations in ocean bottom pressure (Gross 2000). The high accuracy geodetic data (primarily VLBI) were taken from 1985 through 1996, giving enough of the 433 day cycles to have reasonable statistics on both the EOP data and atmosphere data. Ocean global circulation models, however, did not become sufficiently accurate until over a decade after the VLBI data collection was begun. With the excitation source now better understood, the mantle properties can be investigated further. This is a clear case where the value of the historical data was not realized until years after the observations were made.

A similar situation applies to the impact of the nutation measurements on the model for the core and the mantle. The VLBI nutation data from 1984 through 2000 were used by MHB to estimate several specific geophysical parameters for the dynamic properties of the whole earth and the core, and for the magnetic properties of the fluid outer core and the solid inner core. These properties are not accessible by any other set of measurements and can be improved only by extending and improving the current nutation series.

Another area of geophysical interest is the anelasticity of the mantle. Because the out-of-phase components of nutation increase with increasing period according to current models, the best constraint on mantle anelasticity will be obtained by observations spanning multiples of full cycles of the 18.6 year nutation term. The most useful VLBI data began in 1984, so we are almost there for the first cycle. Other information on anelasticity of the mantle, e. g. the amplitudes of the fortnightly variations of UT1, can be obtained from data near the middle of the temporal spectrum. Although at present the estimation of the anelasticity at this period is limited by our understanding of the oceans and atmosphere, modeling of these “spheres” is likely to improve with time until eventually the limit to further modeling gains will be the VLBI measurement accuracy.

Sea level and climate studies also require long historical records. The separation of ocean level change from solid earth is dependent on the accuracy of the long term geodetic record provided by the Terrestrial Reference Frame of VLBI. An accuracy (not just precision) over decades of better than 1 mm per year in height change is needed, and this can only be provided if the underlying TRF scale from VLBI is accurate at that level.

6. Potential for Accuracy Improvement

As with any new experimental technique the accuracy of VLBI improved rapidly in the first few years of development. Since the first generation of specifically geodetic measurements in the early 1970’s, the fractional accuracy of VLBI baseline length measurements has improved by two orders of magnitude. These improvements have been achieved by a combination of instrumental and observation technique changes. The instrumental improvements have been better receivers and telescopes, wider bandwidth, and higher data rates. Observationally, changes have been made primarily to better estimate and thus remove the effects of the neutral atmosphere. These improvements are independent of the geophysical and astronomical modeling changes that have continued concurrently. With a conservative projection for future improvement it is reasonable to expect to achieve a demonstrable accuracy with VLBI of ~2 mm for the length of trans-continental (5000 km) baselines in a single twenty-four hour experiment in the next decade. The corresponding horizontal accuracy for each site is approximately 1 mm, and the vertical accuracy will be reduced to about 4 mm.

Significant improvement in nutation accuracy is expected as well. The median observation uncertainties for nutation from the geodetic VLBI program for the years 1985 through 2001 are shown in Figure 1. These represent the uncertainties of the data for this period used by MHB (they actually used data from 1979 through 1999) to construct the new nutation series and to obtain new estimates for physical features of the Earth's interior. The projection beyond 2001 indicates the uncertainties that are achievable with currently available VLBI networks of eight and sixteen stations. Eight station networks are planned for 2003 if sufficient resources are available. Efficient use of larger networks will require changes in correlator configuration and additional resources for observing. These accuracies can reduce the geophysical model uncertainties significantly.

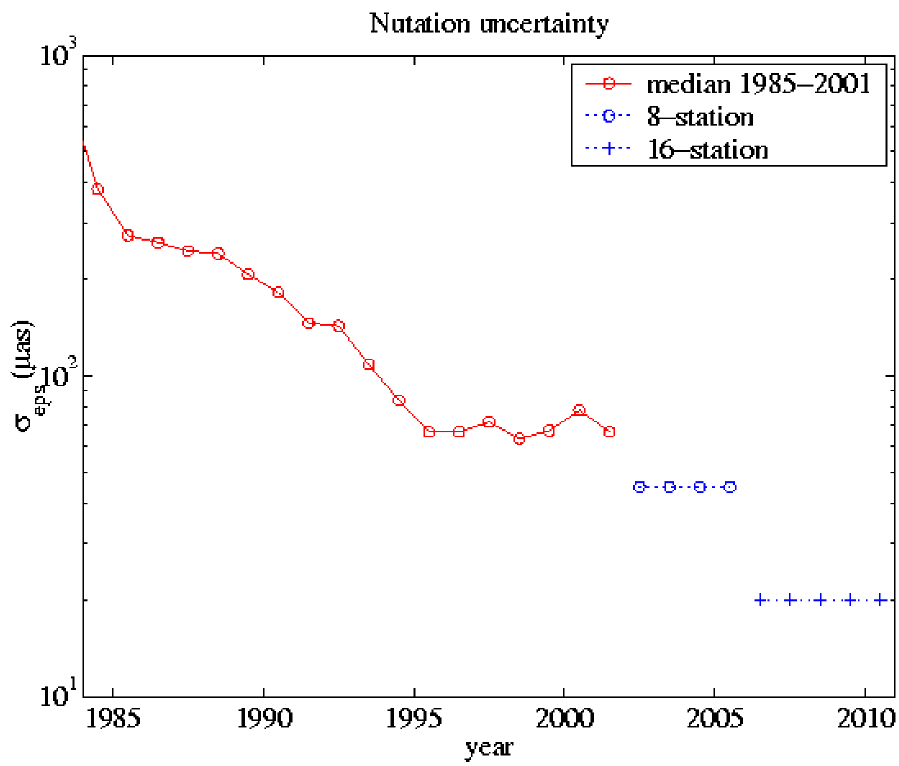

Figure 1. For 1985 – 2001, approximately the median daily observation uncertainties in nutation used to derive MHB2000. The uncertainties beyond 2001 are achievable with current eight- and sixteen-station VLBI networks.

Just as the higher accuracy nutation data for the past ten years allowed estimation of entirely new features of the Earth's interior, namely the magnetic coupling between the fluid core and its adjacent layers, the dramatic improvement in accuracy might also lead to the discovery or investigation of previously unexpected phenomena. On the other hand, the ability to directly estimate geophysical parameters from the nutation data by

MHB opens the door for a quantitative determination of the observing requirements needed to improve our knowledge of these parameters.

These projected improvements will be achieved by a combination of technology, observation techniques, and advances in geophysical and mechanical modeling and measurement. Three known possibilities for improving the accuracy of the observations are a) increasing the size of the VLBI networks, b) implementation of the Mark 5 VLBI data acquisition system, which will increase the recorded bandwidth, and c) implementation of the use of phase delays. The added accuracy from b) and c) will lead to better modeling, particularly of the atmosphere.

There are also needs for improving the timeliness of the results. Almost daily measurements of UT1 by short duration VLBI sessions provide the basis for the rapid prediction of this parameter by the IERS. The elapsed time from observation to product for this parameter, currently approximately five days, can potentially be reduced to less than one hour with the successful implementation of e-vlbi, which will make use of real-time high bandwidth internet transmission of the VLBI data.

Geophysical modeling improvements are expected in the areas of hydrology, atmosphere, and oceans. These areas are receiving attention from NASA both through other programs and through IERS' Global Geophysical Fluids Center (at Goddard) and its Special Bureaus (Chao et al., 2000). Independent of both the fundamental measurement system and the geophysical modeling, if we are to achieve accuracy at the millimeter level, the instruments used as sensors, the VLBI antennas, the SLR telescopes, and the GPS antennas, must be related to a common reference point on the ground.

7. The Observing Program

What does all this say about a geodetic VLBI observing plan that will provide both the unique measurements that will contribute directly to NASA's interest in the science of the Earth's interior and the infrastructure measurements needed to enable the science that can be obtained from the other space geodetic systems?

Results over the past decade indicate that the best precision for both the TRF and EOP are obtained when the number of stations in an observing session is largest (for comparable geographical coverage and antenna sensitivity). When this network requirement is combined with the primary values of VLBI, the resulting program would have all sites observing as often as justified by the science. This is not feasible both because of funding constraints and because of other commitments by some antennas of the international network. Therefore the size of the networks designed to satisfy each of the different observing requirements must be maximized taking into account the frequency of observation and the correlator and station resources.

The TRF should be improved by increasing the accuracy for all sites, by monitoring temporal changes in the site positions, and by improving the tie of the instruments to reference marks on the ground and to any collocated GPS, SLR, or other geodetic systems. In order to maintain a vertical rate accuracy of 1 mm/year within, for example, a five year interval, assuming that the height uncertainty is 8 mm per 24-hour session and that the error is random, approximately six sessions per year are needed.

The CRF is composed of extragalactic radio sources whose positions are determined by VLBI. These sources are variable and must be monitored for strength and for structural complexity, and additional suitable objects must be discovered in source-deficient parts of the sky. Monitoring is achieved primarily through the frequent geodetic observing program, but less than one-third of the currently qualified sources are used regularly. Therefore other observing sessions must be allocated to maintain the astrometric reference frame that is the basis of the International Terrestrial Reference Frame.

Clearly the weekly NEOS-type series must be maintained, but with improved accuracy. From a geophysical point of view the value of such a series is spectacularly demonstrated by the inferences of the MHB2000 model. Furthermore, these observations, now conducted under the auspices of the IVS, provide the fundamental measurements of EOP for the international community through the IERS. Because the EOP series is expected to be reliable and continuous, any transition to higher accuracy must be made with sufficient overlap that unanticipated changes are minimized. This can be accomplished by initiating a second, weekly, NEOS-type series with the greater accuracy but with the same accountability and reliability. In order to maximize the accuracy, the networks should consist of at least eight stations, the maximum number that can be correlated efficiently with the current correlator configurations.

Estimates of the time-variable RFCN amplitude by Herring, Mathews, and Buffett (2001), which cover to the end of 2000, show only slow variation within the uncertainties obtained for an annual estimate, although the phase jumped by approximately 130° in the final year. However, estimation of the RFCN amplitude and phase for the following year (Herring, private communication) confirms the large phase jump and indicates an amplitude change by a factor of five. Reduction of the nutation angle uncertainties while maintaining (or improving) the temporal coverage will be required to determine how rapidly the RFCN changes occur.

While the weekly measurement program satisfies requirements of the nutation series for determining the properties of the core, and the fortnightly UT1 measurements provide data for the estimation of mantle anelasticity, more frequent observations, up to and including a continuous record, would improve the probability of capturing episodic events, such as variations in EOP due to earthquakes or to excitation by coronal mass ejection from the sun, as well as provide the data to detect, verify, and improve the accuracy of diurnal and sub-diurnal effects.

A limited number of high accuracy geodetic experiments are needed to evaluate and demonstrate advances in technique or technology. The monthly R&D experiments, conducted from 1987 through 1995, have provided an important data set that has been used, for example, to evaluate models for estimating the atmospheric delay. These R&D sessions will generally utilize the best systems and should include eight sites to make optimum use of the correlators.

A different type of multi-session experiment has been designated CONT, for CONTINUOUS, and typically lasts from several days to two weeks with the same network of stations. These sessions have been initiated both to provide high accuracy Earth Orientation parameters, for example to study the daily and sub-daily effects of ocean tides in the 1994 CONT series, and to evaluate seasonal variability through comparison of site location repeatability at different times of the year.

An aspect of the geodetic program to be emphasized is the need for NASA to continue its commitment to support both a long-term program and the infrastructure necessary to provide the observations, analysis, maintenance, and improvement. Fifteen countries are committed to the IVS and provide observing time, analysis facilities, and development funds for technological improvement. While this long-term commitment is not typical of the NASA structure of research-development-implementation-analysis-termination for research programs, it is similar to the dedicated support of the Deep Space Network for planetary research.

Summary

An important component of NASA's Earth Science Enterprise is the integrated program to understand the physical state and evolution of the Earth with an emphasis on the solid surface and the impact that changes in that surface have on human existence. Such an understanding will one day help us predict the threats to society from earthquakes, volcanoes, the rise of sea level, and climate change. The fundamental framework for the study of all of these processes is the high accuracy definition of the surface as determined by geodetic measurements using VLBI, SLR, and GPS.

VLBI has three important attributes:

- unique determination of the celestial reference frame and the orientation of the Earth in that frame
- accuracy
- long-term stability

Only through these VLBI measurements can many of the properties of the Earth's interior be determined, such as:

- dynamical oblateness of the core-mantle boundary
- magnetic properties of the inner and outer cores
- anelasticity of the mantle

The VLBI definition of the scale of the TRF, measurement of UT1-UTC, and the long term stability of the reference system and orientation of Earth in space are fundamental requirements for the geodetic measurements by all other techniques. However, it is the complementary utilization of the primary benefits of each that enables the determination of such things as changes in sea level, measurement of water vapor in the atmosphere, and tectonic deformations.

The technological developments that have brought VLBI to its present level of accuracy, and that will enable further improvement in both accuracy and timeliness, are the result of international collaboration and support, but led primarily by the NASA team. Current efforts to make use of new developments in high bandwidth communication and the accelerating capability of off-the-shelf data storage capability will further enhance the accuracy and usability of the VLBI science and service.

VLBI systems were initially developed and enhanced with science goals in mind. The revolutionary new technique, enabled by the development of atomic frequency standards, opened the door to the study of the nuclear regions of galaxies and the discovery of quasars and to verification of the new theory of plate tectonics. However, as with most new instruments, the serendipitous applications are often surprising. Who would have guessed that this astronomical instrument for studying the far reaches of the universe would serve as an instrument for navigation, but for NASA's missions to the planets rather than flights across the Atlantic? In fundamental science, VLBI has provided some of the most compelling measurements to verify the validity of General Relativity.

No other instrument provides information on such a range of scales and phenomena, from the edge of the Universe to the core of the Earth, and from the source of radiation in quasars to the magnetic fields of the inner and outer cores. While the initial development of VLBI for geophysics sought information primarily about the surface and integrated properties of the solid Earth, the increase in sensitivity and accuracy has opened the window to the Earth's interior. Thus the focus has moved inward, and observations over the next decades will further enhance our knowledge of the core and its interface with the mantle the way the past decades have dealt with the surface. However, these observations can be only a part of an integrated program that combines other geodetic techniques as well as seismic and magnetic studies and integrated atmosphere and ocean models.

All of this requires a dedicated program, and the global support for the value of the geodetic function of VLBI is indicated by the formation and wide participation in the International VLBI Service for Geodesy and Astrometry (IVS). Thus the continued and dedicated support by NASA of an active program in geodetic VLBI will both benefit NASA's objectives under the Earth Science Enterprise and provide an improved framework for the discoveries yet to come.

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